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ROYAL SIGNALS AND RADAR ESTABLISHMENT MALVERN (ENGLAND) F/G 20/6
ANOMALOUS REFLECTIVITY LOSSES OF COATED MIRRORS USED IN THE INF--ETC(U)
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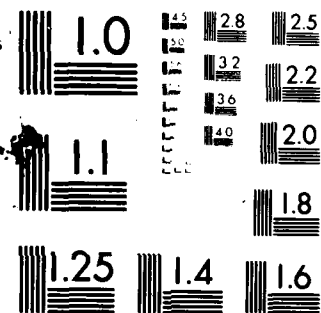
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ROYAL SIGNALS AND RADAR ESTABLISHMENT

Memorandum 3360

Title: ANOMALOUS REFLECTIVITY LOSSES OF COATED MIRRORS USED IN THE INFRARED

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Date: January 1982

SUMMARY

It has recently been found that front-surfaced aluminium mirrors coated with a variety of thin protective layers have severe reflectivity losses when used at non-normal angles of incidence between 8 and 12 μm . This memorandum gives the mechanism for this anomalous loss and derives the condition that the loss will occur if $\cos \phi_0 < (n_1^2 + k_1^2)^{-1/2}$ where ϕ_0 is the angle of incidence. Three materials proposed to replace the conventional oxides of silicon as protective coatings, and the reflectivity losses of tarnished aluminium mirrors, are discussed in section 4.

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ANOMALOUS REFLECTIVITY LOSSES OF COATED MIRRORS USED IN THE INFRARED

G J Ball

LIST OF CONTENTS

- 1 Introduction
- 2 Mechanism for the Reflectivity Loss
- 3 Variation with Thickness
- 4 Summary and Discussion
 - 4.1 Mechanism for the Reflectivity Loss
 - 4.2 New Materials
 - 4.3 Mirror Tarnishing

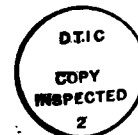
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References

1 INTRODUCTION

The reflectivities at near-normal incidence of uncoated front-surfaced aluminium mirrors and of aluminium mirrors coated with thin layers of the oxides of silicon as protection have often been measured in the 8-12 μm spectral region and found to be approximately equal. From this it was generally accepted that, like bare aluminium mirrors, protected mirrors could also be used at angles of incidence without a marked decrease in reflectivity. However it has recently been shown^{(1), (2)} that mirrors with such protecting coatings can have pronounced reflectivity losses when used at non-normal incidence. To illustrate this Table 1 gives the total reflectivity for unpolarised light R and the reflectivity components for light parallel and perpendicular to the plane of incidence (R_p and R_s) calculated for bare aluminium and aluminium coated with thin layers of SiO and SiO_2 for angles of incidence ϕ_0 of zero, 45 and 60 degrees. Most of the calculated values are also displayed in Fig 1 and Fig 2. Experimental observations of anomalous reflectivity losses are discussed in the next

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paragraph. From Table 1 and the experimental observations it can be seen that the losses occur for only one direction of polarisation R_p , and are not found at normal incidence. Also that the reflectivity of bare aluminium does not exhibit any similar losses - its reflectivity R decreases by only 0.5% between $\phi_o = 0^\circ$ and $\phi_o = 60^\circ$ in the wavelength range 8-12 μm . The minimum value of R_p calculated for $\text{Al} + \text{SiO}_2$ at an angle of incidence of 60° is 2.3% at a wavelength of 8.075 μm (not given in Table 1).

Experimental work exhibiting this anomalous loss has been published by several authors. For example reflectivity losses can be clearly seen in the reflectivity spectra between 8 and 12 μm of aluminium coated with a mixture of the oxides of silicon (SiO_x) which have been published by Pellicori⁽²⁾. He found a minimum reflectivity R of about 80% in this spectral range at an angle of incidence of 45° . Other reflectivity measurements of $\text{Al} + \text{SiO}_x$ by Cox and Hass⁽⁵⁾ found minima of 71% at $\phi_o = 45^\circ$ and 54% at $\phi_o = 60^\circ$. The experimentally measured reflectivity of commercially available protected aluminium (measured for us by SIRA institute⁽³⁾) is illustrated in Fig 2 for comparison with the spectra calculated for $\text{Al} + \text{SiO}$ and $\text{Al} + \text{SiO}_2$. The coating on the commercial sample is usually a mixture of the oxides of silicon. The commercial sample exhibited reflectivity losses in the same wavelength region as the losses calculated for $\text{Al} + \text{SiO}$ and $\text{Al} + \text{SiO}_2$ (see Fig 2).

The anomalous loss has also been observed in the spectra of other protective coatings and front-surfaced metallic reflectors, eg MgF_2 on aluminium⁽²⁾, commercially available protected silver^{(2),(3)}, and Al_2O_3 on aluminium⁽⁴⁾. This last example is relevant to the tarnishing of unprotected aluminium mirrors by oxidation, and is discussed in section 4.

Although the oxides of silicon are commonly used as protective coatings for freshly deposited aluminium mirrors - as they are durable, prevent tarnishing and give protection against humidity and abrasion - their use in systems operating between 8 and 12 μm at non-normal angles of incidence can lead to considerably reduced reflectivities.

It is the purpose of this memorandum to give the mechanism for the reflectivity loss - none has been previously reported - and its dependence on parameters such as the angle of incidence, the optical constants, and the thickness of the coating. Section 4 contains a summary of the mechanism and its relevance to mirror tarnishing, and it also examines three materials recently proposed as protective coatings to replace the oxides of silicon for use in the 8-14 μm waveband.

This memorandum provides the theoretical basis for a more applied RSRE memorandum, number 3295⁽¹⁰⁾, on the protection of front surfaced aluminium mirrors with diamond like carbon coatings for use in the infrared. This has been previously released.

2 MECHANISM FOR THE REFLECTIVITY LOSS

A mechanism for the reflectivity loss has not been given by previous authors, but they have noted the following:

- a The losses occur only for light parallel to the plane of incidence, and are not found at normal incidence.
- b The effect depends entirely on the dielectric layer and not the metallic mirror⁽⁴⁾.
- c The reflectivity decrease is most severe when the refractive index of the dielectric $n_1 < 1$ and its extinction coefficient k_1 is small⁽¹⁾ (the complex refractive index $N_1 = n_1 - ik_1$). Such conditions exist typically on the short wavelength side of reststrahlen bands.
- d No interference effects due to the layer were expected as the optical thickness of the protective layer is less than one tenth of a quarter wavelength at $10 \mu\text{m}$ ⁽⁵⁾.

The reflectivity of a metal overcoated with a single dielectric layer may be calculated if the optical constants of both are known. From values of the refractive index (n) and extinction coefficient (k) for aluminium, SiO and SiO₂ tabulated by Cox et al⁽¹⁾ (from the original references (6), (7) and (8) respectively) the total reflectivity for unpolarised light (R) and, where appropriate, the reflectivity components parallel (R_p) and perpendicular (R_s) to the plane of incidence for bare aluminium and aluminium coated with 1500 Å thicknesses of SiO and SiO₂ have been calculated and are given in Table 1. They are identical to the calculations previously reported by Cox et al⁽¹⁾, and the effect of the reflectivity loss on R_p at non-normal incidence can be clearly seen.

In order to understand the mechanism for the reflectivity loss analytical studies and computer calculations of the phase and amplitude relationships for light waves at the air-dielectric and dielectric-metal interfaces were undertaken, from which it was concluded that the loss is due to destructive interference between light reflected from the two interfaces.

The metals of interest have optical constants in the infrared such that the Fresnel coefficient r_2 for reflection at a dielectric-metal boundary for light parallel to the plane of incidence can be approximated to by -1 , and thus the phase change on reflection ψ_2 by π , for angles of incidence of practical importance. At the air-dielectric boundary the phase change on reflection, again for light parallel to the plane of incidence (the p component), is between π and $\pi/2$ for angles of incidence below an angle ϕ' - where ϕ' is defined as the angle at which the phase change equals $\pi/2$ - and between $\pi/2$ and zero for angles of incidence above it. The thickness of the protecting layers under discussion is too small to give appreciable absorption or path difference effects, even when there is a strong absorption peak in the dielectric. However, in the spectral region near a strong absorption peak the optical constants of the dielectric (n_1 and k_1) have values which reduce ϕ' to small angles of incidence. Therefore the phase change on reflection at higher angles of incidence at the air-dielectric boundary has a value to cause destructive interference with light reflected from the dielectric-metal boundary and give a reflectivity loss. Severe losses can result if the phases of the two reflected waves are near antiphase, that is if the phase change on reflection at the air-dielectric boundary is close to zero. The angle ϕ' is usually close to the principal angle - defined as the angle of incidence at which the difference between the phase changes on reflection of the s and p components equals $\pi/2$ - because the phase change for the s component is approximately π for most of the values of the angles of incidence and optical constants under discussion.

From the above, destructive interference will occur if a single-coated mirror is used at an angle of incidence greater than ϕ' (ie $\phi_0 > \phi'$), and values of the optical constants of a coating for which this condition is satisfied can be found by first calculating the angle ϕ' as a function of n_1 and k_1 .

The complex Fresnel coefficient for reflection at the air-dielectric interface for light parallel to the plane of incidence is given by:

$$r_{1p} = \frac{N_0 \cos \phi_1 - N_1 \cos \phi_0}{N_0 \cos \phi_1 + N_1 \cos \phi_0} \quad (1)$$

where ϕ_0 and ϕ_1 are the angles of incidence and refraction in air and the dielectric, $N_1 (= n_1 - ik_1)$ is the complex refractive index of the dielectric, and $N_0 (= 1.0)$ that of air. The phase change on reflection ψ_1 may be derived

from eqn (1) in the form:

$$\tan \psi_1 = \frac{2 \cos \phi_0 \left[k_1 C_R - n_1 C_I \right]}{|\cos \phi_1|^2 - |N_1 \cos \phi_0|^2} \quad (2)$$

where $\cos \phi_1 = C_R - iC_I$. Note that if the dielectric layer is non-absorbing then k_1 and, consequently, C_I both equal zero so that the phase change on reflection is π for all ϕ_0 and no destructive interference can occur.

For absorbing layers it can be seen from eqn (2) that the angle ϕ' at which $\psi_1 = \pi/2$ and $\tan \psi_1$ equals infinity occurs when

$$|\cos \phi_1|^2 = |N_1 \cos \phi'|^2 \quad (3)$$

Eqn (3) may be rewritten by substitution for ϕ_1 from Snell's law and putting $N_1 = n_1 - ik_1$ as

$$\left(n_1^2 + k_1^2 \right)^2 \cos^2 \phi' = \left[\left(n_1^2 - k_1^2 - \sin^2 \phi' \right)^2 + 4n_1^2 k_1^2 \right]^{\frac{1}{2}} \quad (4)$$

Eqn (4) can be solved by first squaring both sides and then substituting $(1 - \sin^2 \phi')^2$ for $\cos^4 \phi'$ to give:

$$\begin{aligned} \sin^4 \phi' \left[1 - \left(n_1^2 + k_1^2 \right)^4 \right] + 2 \sin^2 \phi' \left[\left(n_1^2 + k_1^2 \right)^4 - \left(n_1^2 - k_1^2 \right)^2 \right] \\ + \left(n_1^2 + k_1^2 \right)^2 - \left(n_1^2 - k_1^2 \right)^4 = 0 \end{aligned} \quad (5)$$

The solution to which is

$$\sin^2 \phi' = - \frac{b \pm (b^2 - 4ac)^{\frac{1}{2}}}{2a} \quad (6)$$

where

$$\begin{aligned} a &= 1 - \left(n_1^2 + k_1^2 \right)^4 \\ b &= 2 \left[\left(n_1^2 + k_1^2 \right)^4 - \left(n_1^2 - k_1^2 \right)^2 \right] \end{aligned}$$

$$c = \left(n_1^2 + k_1^2\right)^2 - \left(n_1^2 + k_1^2\right)^4$$

In eqn (6) the positive root is taken to calculate ϕ' and the calculation is simplified by first calculating $(n_1^2 + k_1^2)$ and $(n_1^2 - k_1^2)$. From computer studies an approximate solution to eqn (4) was found to be

$$\cos \phi' = \left(n_1^2 + k_1^2\right)^{-\frac{1}{2}} \quad (7)$$

The validity of this approximation is discussed later in the section.

The condition for destructive interference to occur, that $\phi_o > \phi'$, may be rewritten using eqn (7) as

$$\cos \phi_o < \left(n_1^2 + k_1^2\right)^{-\frac{1}{2}} \quad (8)$$

so that the condition for destructive interference may be found without first calculating ϕ' .

In Table 2 values of ϕ' are calculated using eqns (6) and (7) from the optical constants of SiO and SiO₂ given in Table 1. A few sample calculations for aluminium are also included. For nearly all the tabulated values the angle ϕ' calculated from the exact solution of eqn (6) and the approximate one of eqn (7) are in close agreement. If there is no solution the phase change on reflection is between $\pi/2$ and zero for all angles of incidence. Also shown in Table 2 is the phase change of the reflected s component at ϕ' . For most of the tabulated values this is about 180° showing that ϕ' is close to the principal angle, as discussed earlier in this section.

To summarise: if a single-coated mirror is used such that the condition $\phi_o > \phi'$, or its equivalent expressed in eqn (8), is satisfied then destructive interference will occur between the p components of light reflected from the air-dielectric and dielectric-metal boundaries. Note that these conditions predict the occurrence of maximum reflectivity losses only, where the phase difference between the two reflected waves is between $\pi/2$ and zero. Some destructive interference and a reflectivity loss can also occur if the phase difference is greater than $\pi/2$.

The conditions for reflectivity loss depend not only on the phase difference between the waves reflected from the two boundaries, but also on their relative amplitudes. The final magnitudes and wavelength ranges of reflectivity losses are a function of five variables - the optical constants (n_1 and k_1), the coating thickness d , the angle of incidence ϕ_0 and the wavelength λ - as the reflectivity of the p component R_p is given by the equation⁽⁹⁾:

$$R_p = \frac{(g_1^2 + h_1^2)e^{2\alpha} + (g_2^2 + h_2^2)e^{-2\alpha} + 2(g_1g_2 + h_1h_2)\cos 2\gamma + 2(g_1h_2 - g_2h_1)\sin 2\gamma}{e^{2\alpha} + (g_1^2 + h_1^2)(g_2^2 + h_2^2)e^{-2\alpha} + 2(g_1g_2 - h_1h_2)\cos 2\gamma + 2(g_1h_2 + g_2h_1)\sin 2\gamma} \quad (9)$$

where g_1 and g_2 are the real and h_1 and h_2 the imaginary parts of r_1 and r_2 respectively and

$$\alpha = \frac{2\pi d}{\lambda} \text{Im}(N_1 \cos \phi_1) \quad \gamma = \frac{2\pi d}{\lambda} \text{Re}(N_1 \cos \phi_1)$$

The equivalent conditions expressed by either $\phi_0 > \phi'$ or eqn (8) may be applied to the data recorded in Table 1 to predict wavelength ranges in which severe reflectivity losses will occur. If ϕ_0 is set equal to 60° the predicted wavelength ranges are 8.4 to 9.6 μm for Al + SiO and 8.0 to 8.8 μm for Al + SiO₂ (see Table 2). The total reflectivities of Al + SiO and Al + SiO₂ for $\phi_0 = 60^\circ$ are plotted in Fig 1 from which it can be seen that there is excellent agreement between the predicted wavelength ranges and maximum reflectivity losses.

3 VARIATION WITH THICKNESS

Fig 3 and Fig 4 show the reflectivity component R_p calculated for aluminium overcoated with SiO as a function of coating thickness. The reflectivity R_p was calculated at a wavelength of 8.8 μm , in the region of pronounced reflectivity loss, for angles of incidence of nought, 45 and 60 degrees. At the non-zero angles of incidence there is a rapid decrease in R_p with increasing thickness, the rate of which falls as the thickness increases, such that a constant low value of R_p is found for large thicknesses (Fig 4).

A detrimental decrease in reflectivity occurs even at very small thicknesses of the coating (Fig 3). For thicknesses of less than 2000 Å R_p has an approximately linear dependence on d which it is the purpose of the remainder of this section to explain.

Consider eqn (9) for small thicknesses of SiO on aluminium at $\lambda = 8.8 \mu\text{m}$ and $\phi_0 = 60^\circ$. As discussed in section 2, r_2 is approximately equal to -1 and calculations of the quantities α and γ show that $\alpha \ll 1$ and γ is small such that eqn (9) may be written as

$$R_p = \frac{1 + r_1 r_1^* - 2g_1 - [2\alpha(1 - r_1 r_1^*) - 2h_1 2\gamma_1]}{1 + r_1 r_1^* - 2g_1 + [2\alpha(1 - r_1 r_1^*) - 2h_1 2\gamma_1]}$$

This equation is one of the form

$$R_p = \frac{a - bd}{a + bd} \quad (10)$$

where a and b are constants for constant ϕ_0 and λ (and hence N_1). As $bd/a \ll 1$ eqn (10) can be expanded and approximated to by

$$R_p = 1 - \frac{2bd}{a} + \text{terms} \quad (11)$$

Eqn (11) predicts a linear decrease of R_p from a value of one and agrees well with the behaviour of R_p as a function of d in Fig 3. That the decrease in R_p is not only due to an increase in the absorption of the dielectric is shown in Fig 4 where the internal absorption of SiO ($= \exp(-2\alpha d)$) is also plotted as a function of thickness.

4 SUMMARY AND DISCUSSION

This section contains a summary of the mechanism for the reflectivity loss, discussion on three materials proposed to replace the oxides of silicon as protective coatings in the 8-14 μm band, and the relevance of reflectivity losses to tarnished mirrors.

4.1 MECHANISM FOR THE REFLECTIVITY LOSS

The anomalous reflectivity loss at non-normal incidence of metallic mirrors coated with a single dielectric layer was found to be due to destructive interference between light reflected from the air-dielectric and dielectric-metal interfaces. The losses appear to be significant only for light parallel to the plane of incidence (the p component).

In the infrared the optical constants of the metals of interest are such that the Fresnel coefficient for the p component of light reflected

from the metal-dielectric boundary is approximately -1 , and hence the phase change on reflection approximately π , for angles of incidence of practical importance. The thickness of the coating is too small to give appreciable absorption or path-difference effects, and therefore severe destructive interference can occur if the phase change at the air-dielectric boundary is close to zero. The magnitude of any reflectivity loss will also depend on the relative amplitudes of the interfering waves.

An angle ϕ' was defined as the angle of incidence at which the phase change on reflection at the air-dielectric boundary for light parallel to the plane of incidence equals $\pi/2$. For angles of incidence less than ϕ' the phase change is between π and $\pi/2$, and for angles greater than ϕ' it is between $\pi/2$ and zero. This severe destructive interference will occur if ϕ' is reduced below angles of incidence of practical importance, that is if the condition that $\phi_0 > \phi'$ is satisfied where ϕ_0 is the angle of incidence. Equations from which ϕ' can be calculated if the refractive index n_1 and extinction coefficient k_1 of the dielectric are known (eqns (4), (5) and (6)) were derived from analysing the phase change on reflection as a function of n_1 and k_1 . From eqn (4) a condition equivalent to that for destructive interference, $\phi_0 > \phi'$, was found to be $\cos \phi_0 < (n_1^2 + k_1^2)^{-1/2}$, and therefore maximum reflectivity losses can be predicted from a simple inequality without first calculating ϕ' . The conditions for destructive interference correctly predicted the wavelengths at which maximum reflectivity losses occurred for aluminium mirrors overcoated with thin layers of SiO or SiO₂ (see section 2).

Typically the optical constants of the dielectric have values that give severe reflectivity losses on the short wavelength side of strong absorption peaks (Reststrahlen bands)⁽⁵⁾, and therefore although thin layers of materials with such peaks in a wavelength range of interest will not have appreciable absorption losses they should not be used as protective coatings for mirrors used at non-normal angles of incidence.

4.2 NEW MATERIALS

Three materials proposed to replace the conventional oxides of silicon as protective coatings in the 8-14 μm waveband - Y₂O₃⁽⁵⁾, HfO₂⁽⁵⁾ and the hard carbon coating developed at RSRE⁽¹⁰⁾ for use in the infrared - are discussed below. In order to be a good protective coating a material must be both durable and have the correct optical properties.

The infrared reflectivity of thin layers (1500 Å) of Y_2O_3 and HfO_2 on aluminium have been measured by Cox and Hass⁽⁵⁾, and Pellicori⁽²⁾ subsequently measured the same samples. The reported spectra showed anomalous reflectivity losses for both $Al + Y_2O_3$ and $Al + HfO_2$ for wavelengths above 12 μm , although the losses were not great. For example the reflectivity R spectra between 2 and 16 μm at an angle of incidence of 45° reported by Pellicori⁽²⁾ show a minimum of 93% at 16 μm for $Al + Y_2O_3$ and 91% at 14 μm for $Al + HfO_2$. A minimum reflectivity R of 77.9% at 14 μm and at an angle of incidence of 60° was observed by Cox and Hass⁽⁵⁾. Although the reported reflectivity losses are not severe it must be ensured that mirrors coated with these materials are not used in conditions where the losses become more pronounced.

The protection of front-surfaced mirrors used in the infrared with the hard-carbon coating developed at RSRE is fully discussed in reference (10) but a brief summary of that work will also be given here.

Techniques have been developed to deposit an abrasion resistant, chemically durable carbon coating with low absorption in the infrared on a variety of metals. Values of n and k for typical carbon layers were derived from transmission and reflection measurements between 3 and 14 μm for layers deposited on germanium substrates. The refractive index n was found to have a value of 2.2 to within experimental error over the specified wavelength range, and values of k between 8 and 14 μm are given in Table 3. The experimental measurements and the values of the optical constants show that there are no strong absorption peaks between 3 and 14 μm , which indicates that there will be no anomalous reflectivity losses.

Reflectivities at wavelengths between 3 and 14 μm of aluminium overcoated with a 1500 Å thickness of the hard carbon coating at angles of incidence of nought, 45° and 60° have been calculated from the optical constants of carbon and aluminium given in Table 3 and Table 1 respectively.

Detailed results of these calculations are given in reference (10), but a summary will also be given here.

The total reflectivity R of aluminium overcoated with a 1500 Å thickness of carbon calculated for unpolarised light at wavelengths between 8 and 14 μm for angles of incidence of nought, 45° and 60° are given in Table 3. The maximum decrease in reflectivity between angles of incidence

of nought and 60° is 0.7%. The absence of any anomalous reflectivity losses is in agreement with the theory presented in this memorandum as the angle ϕ' calculated from eqn (6) using the optical constants of carbon given in Table 3 has a value of 65.6° throughout the 8-14 μm waveband; and so the condition for destructive interference, that $\phi_o > \phi'$, is not satisfied.

Thus the carbon overcoating of metallic reflectors provides coatings that are abrasion resistant, chemically durable and optically very efficient over a wide range of angles of incidence.

4.3 MIRROR TARNISHING

It has been experimentally observed that aluminium mirrors coated with thin (1000 Å) layers of Al_2O_3 exhibit anomalous reflectivity losses at non-normal angles of incidence between 9 and 15 $\mu\text{m}^{(4)}$. Freshly deposited aluminium mirrors tarnish over a period of time by the oxidation of exposed surfaces in air, and this reduces the reflectivity due to absorption in the oxidised surface. The reported work shows that the reflectivity of these mirrors at non-normal angles of incidence can be further reduced by an anomalous loss even though, as shown in section 3, the oxidation layer may be very thin.

ACKNOWLEDGEMENT

I wish to thank Dr A H Lettington for suggesting this topic for research.

REFERENCES

- 1 J T Cox, G Hass and W R Hunter, Appl. Optics 14, 1247 (1975).
- 2 S F Pellicori, Appl. Optics 17, 3335 (1978).
- 3 J L Gresty and T L Williams, to be published.
- 4 J T Cox and G Hass, Appl. Optics 17, 333 (1978).
- 5 J T Cox and G Hass, Appl. Optics 17, 2125 (1978).
- 6 D E Gray (ed), Americal Institute of Physics Handbook, McGraw-Hill, New York (1972).
- 7 G Hass and C D Salzberg, J. Opt. Soc. Am. 44, 81 (1954).
- 8 C Boeckner, J. Opt. Soc. Am. 19, 7 (1929).
- 9 O S Heavens, "Optical Properties of Thin Films", Dover Publications Ltd, New York (1965).
- 10 A H Lettington and G J Ball, RSRE Memorandum No 3295 (1981).

TABLE ONE. OPTICAL CONSTANTS OF AL, SiO AND SiO₂ AND REFLECTIVITIES OF AL AND AL-SiO₂ SYSTEMS

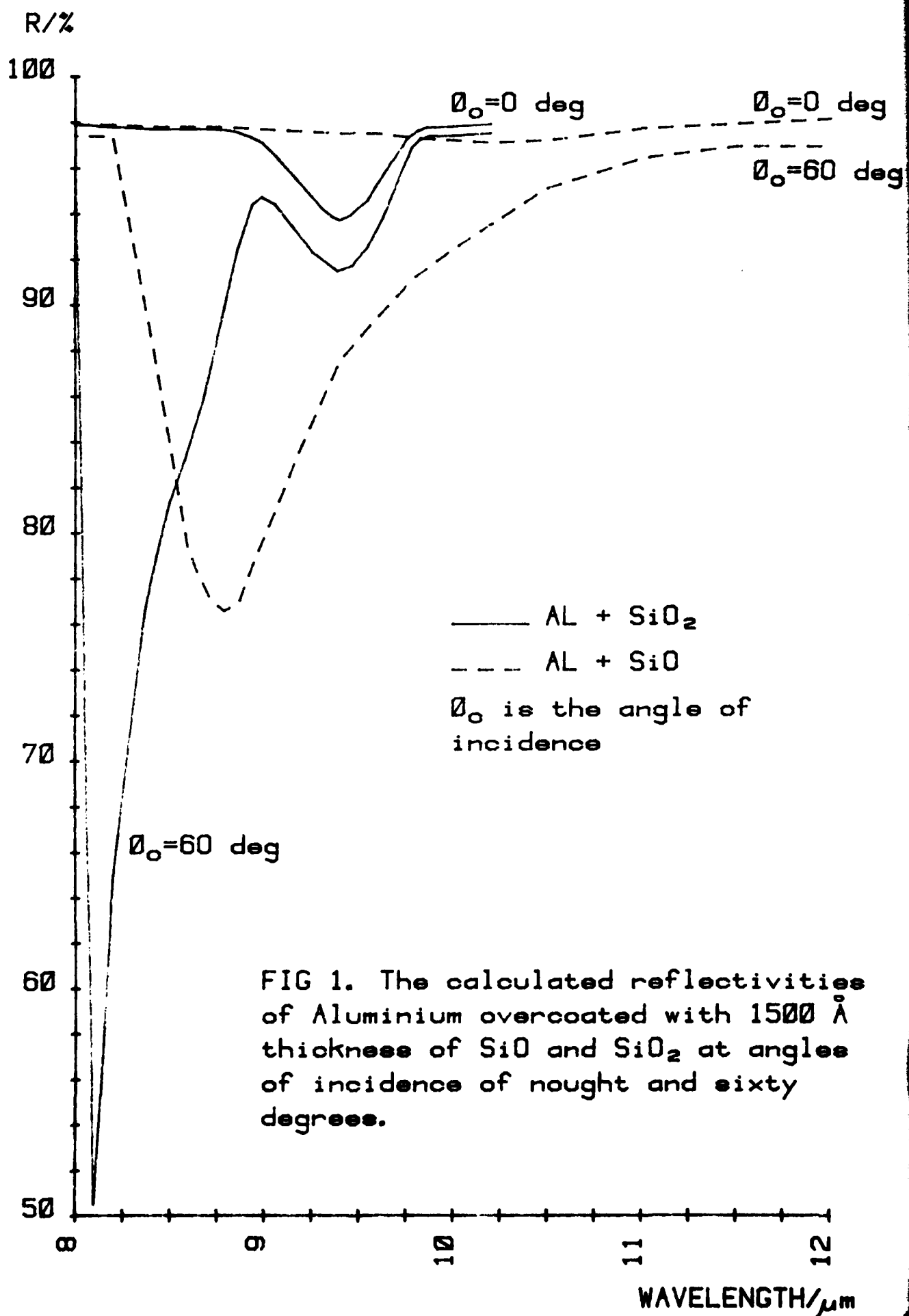
WAVELENGTH (μm)	AL			AL 45°			SiO			AL + SiO (t = 1500Å)			SiO ₂			AL + SiO ₂ (t = 1500Å)		
	n	k	C° R	R	R _p	R	n	k	C° R	R _s	R _p	R	n	k	C° R	R _s	R _p	R
8.0	17.9	55.3	97.9	98.5	97.1	97.8	99.0	95.9	97.5	1.15	0	97.9	98.5	97.0	97.8	98.9	95.9	97.4
8.2	18.8	56.2	97.9	98.5	97.2	97.9	98.9	95.8	97.4	1.04	0	97.9	98.5	97.0	97.8	98.9	95.8	97.4
8.4	19.5	57.5	97.9	98.5	97.1	97.8	99.0	95.9	97.5	0.95	0.13	97.8	98.5	86.5	93.5	98.9	78.6	88.9
8.6	20.3	58.8	97.9	98.5	97.0	97.8	99.0	95.9	97.5	0.87	0.31	97.8	98.4	77.2	87.8	98.9	53.9	72.9
8.8	21.0	60.0	97.9	98.5	97.1	97.8	99.0	95.9	97.5	0.85	0.51	97.8	98.4	74.2	86.3	98.9	54.4	76.7
9.0	21.8	61.1	98.0	98.6	97.1	97.9	99.0	95.9	97.5	0.90	0.70	97.7	98.4	78.0	88.2	98.8	61.0	79.3
9.2	22.5	62.4	98.0	98.6	97.2	97.9	99.0	96.0	97.5	0.96	0.92	97.6	98.3	82.5	90.4	98.8	63.7	83.3
9.4	23.3	63.7	98.0	98.6	97.2	97.9	99.0	96.0	97.5	1.10	1.15	97.5	98.3	86.6	92.5	98.8	76.1	87.5
9.6	24.0	65.0	98.0	98.6	97.2	97.9	99.0	96.1	97.6	1.30	1.25	97.5	98.2	88.8	93.5	98.7	80.1	89.4
9.8	25.0	66.1	98.0	98.6	97.2	97.9	99.0	96.1	97.6	1.60	1.32	97.3	98.1	90.6	94.4	98.6	83.7	91.2
10.0	26.0	67.3	98.0	98.6	97.2	97.9	99.0	96.1	97.6	1.90	1.36	97.2	98.0	91.9	95.0	98.6	86.2	92.4
10.2	26.4	68.2	98.1	98.6	97.3	98.0	99.0	96.1	97.6	2.30	1.33	97.1	97.9	93.0	95.5	98.5	88.4	93.5
10.5	27.5	70.0	98.1	98.6	97.3	98.0	99.0	96.2	97.6	2.80	0.9	97.2	97.0	94.6	96.3	98.6	91.5	95.1
11.0	29.3	72.7	98.1	98.6	97.3	98.0	99.0	96.2	97.6	2.80	0.4	97.7	98.4	96.0	97.2	98.8	93.9	96.4
11.5	31.2	75.3	98.1	98.7	97.4	98.1	99.1	96.3	97.7	2.55	0.23	97.9	98.5	96.5	97.5	99.0	94.7	96.9
12.0	33.1	78.0	98.2	98.7	97.4	98.1	99.1	96.3	97.7	2.12	0.16	98.1	98.6	96.6	97.6	99.0	94.8	96.9

TABLE TWO. VALUES OF ϕ' CALCULATED FROM EQNS (6) AND (7)

Wavelength (μm)	n	k	ϕ' from eqn (6)	ϕ' from eqn (7)	Phase of s components at ϕ' (calculated from eqn (6))
8.0	1.15	0.0	Not applicable as $k = 0.0$		
8.2	1.04	0.0			
8.4	0.95	0.13			
8.6	0.87	0.31			
8.8	0.85	0.51			
9.0	0.90	0.70	30.2	28.7	177.4
9.2	0.96	1.92	40.6	41.2	178.7
9.4	1.10	1.15	50.2	51.1	179.3
9.6	1.30	1.25	56.1	56.3	179.5
9.8	1.60	1.32	61.5	61.2	179.7
10.0	1.90	1.38	65.3	64.8	179.8
10.2	2.30	1.33	68.5	67.9	179.8
10.5	2.80	0.90	71.0	70.1	179.9
11.0	2.80	0.40	70.5	69.3	180.0
11.5	2.55	0.23	68.6	67.0	180.0
12.0	2.12	0.16	64.8	61.9	180.0
8.0	0.35	0.10	No solution		
8.2	0.43	0.58	No solution		
8.4	0.50	0.90	11.3		
8.6	0.48	1.02	22.8		
8.8	0.37	1.30	36.8		
9.0	0.90	2.65	68.1		
9.2	2.20	3.02	74.3		
9.4	3.65	3.00	77.8		
9.6	3.73	1.70	76.1		
9.8	3.25	0.0	Not applicable as $k = 0.0$		
10.0	2.90	0.0			
10.2	2.70	0.0			
8.0	17.90	55.30	89.0	89.0	180.0
9.0	21.80	61.10	89.1	89.1	180.0
9.6	24.00	65.00	89.2	89.2	180.0
11.0	29.30	72.70	89.3	89.3	180.0

TABLE THREE. THE OPTICAL CONSTANTS OF CARBON AND THE TOTAL REFLECTIVITY OF AN Al + C SYSTEM ($d = 1500 \text{ \AA}$)

WAVELENGTH (μm)	REFLECTIVITY R (%)				
	n	k	$\phi_o = 0^\circ$	$\phi_o = 45^\circ$	$\phi_o = 60^\circ$
8.0	2.2	0.046	97.7	97.5	97.0
8.2	2.2	0.046	97.7	97.5	97.0
8.4	2.2	0.047	97.7	97.5	97.0
8.6	2.2	0.048	97.7	97.5	97.1
8.8	2.2	0.049	97.8	97.5	97.1
9.0	2.2	0.049	97.8	97.6	97.1
9.2	2.2	0.050	97.8	97.6	97.1
9.4	2.2	0.051	97.8	97.6	97.1
9.6	2.2	0.052	97.9	97.7	97.2
9.8	2.2	0.052	97.9	97.7	97.2
10.0	2.2	0.053	97.9	97.7	97.2
10.5	2.2	0.055	98.0	97.8	97.3
11.0	2.2	0.057	98.0	97.8	97.3
11.5	2.2	0.059	98.0	97.8	97.4
12.0	2.2	0.061	98.1	97.9	97.4
13.0	2.2	0.065	98.2	98.0	97.5
14.0	2.2	0.068	98.3	98.1	97.6



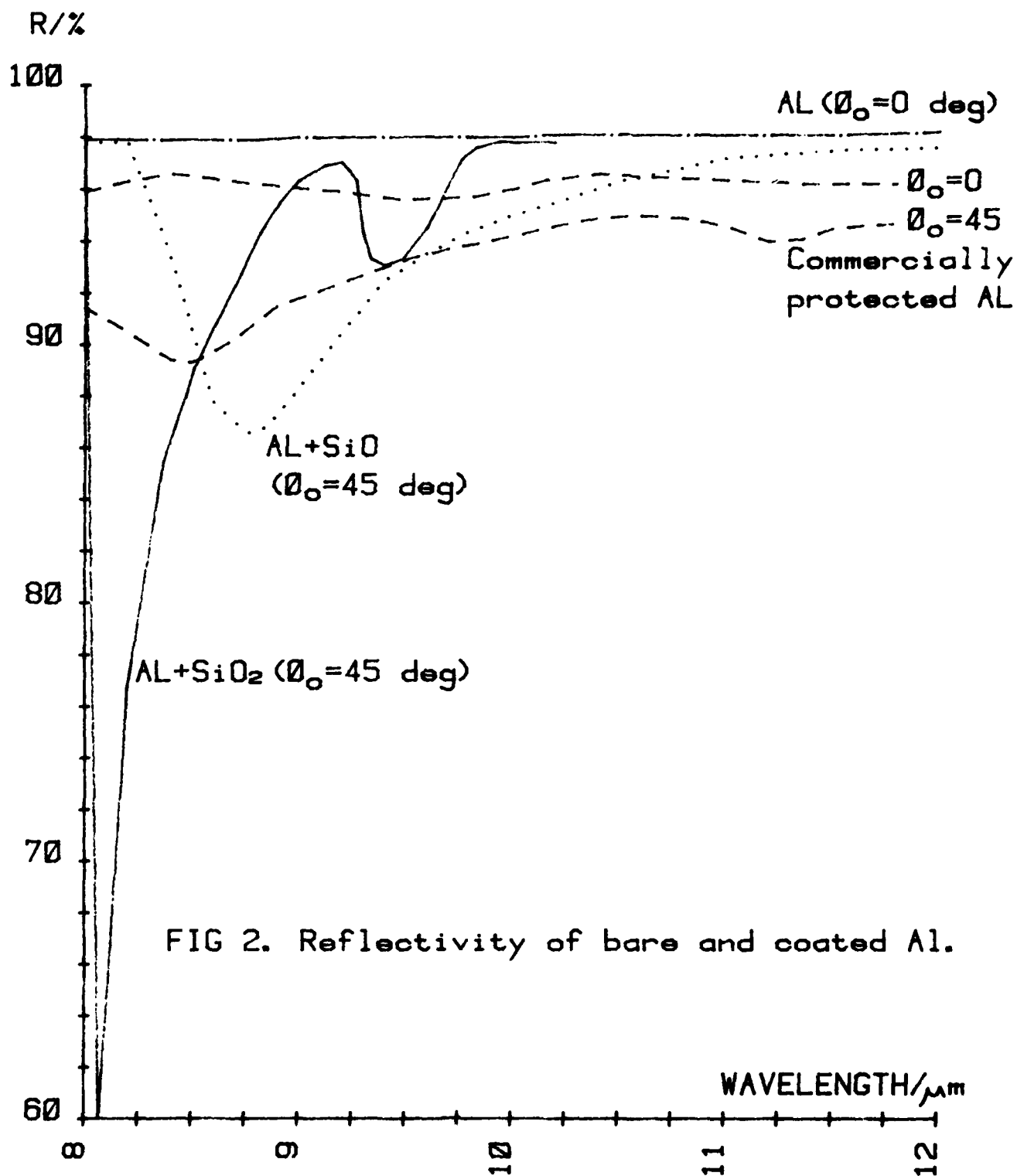


FIG 2. Reflectivity of bare and coated Al.

θ_o is the angle of incidence

— AL (Calculated) $\theta_o = 0$ deg

--- Commercially protected AL $\theta_o = 0$ and 45 deg

..... AL + SiO (Calculated) $\theta_o = 45$ deg

— AL + SiO₂ (Calculated) $\theta_o = 45$ deg

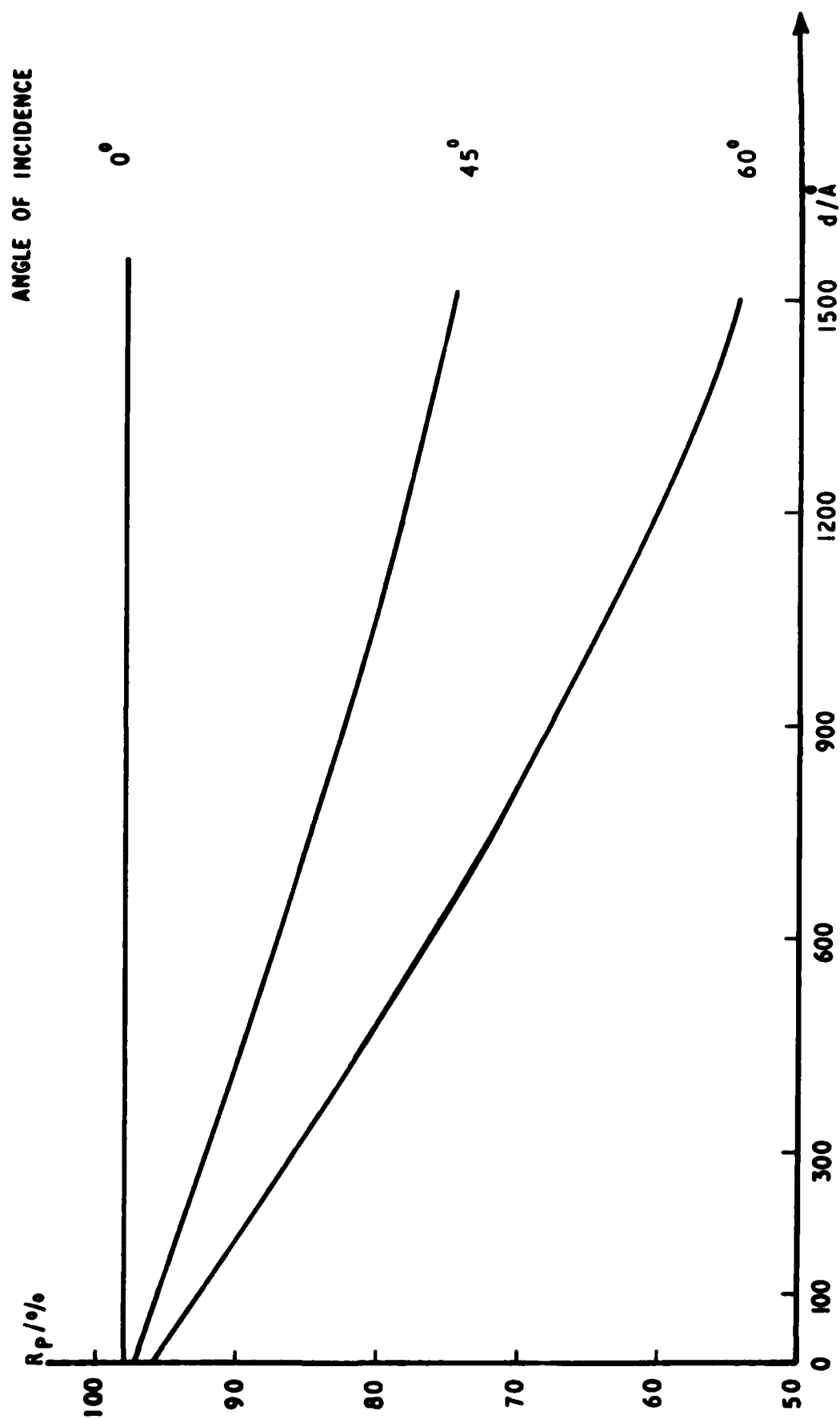


FIG. 3. VARIATION OF R_p WITH THICKNESS FOR ALUMINIUM OVERCOATED WITH SiO AT A WAVELENGTH OF $8.8\text{ }\mu\text{m}$

REFLECTIVITY AND INTERNAL ABSORPTION

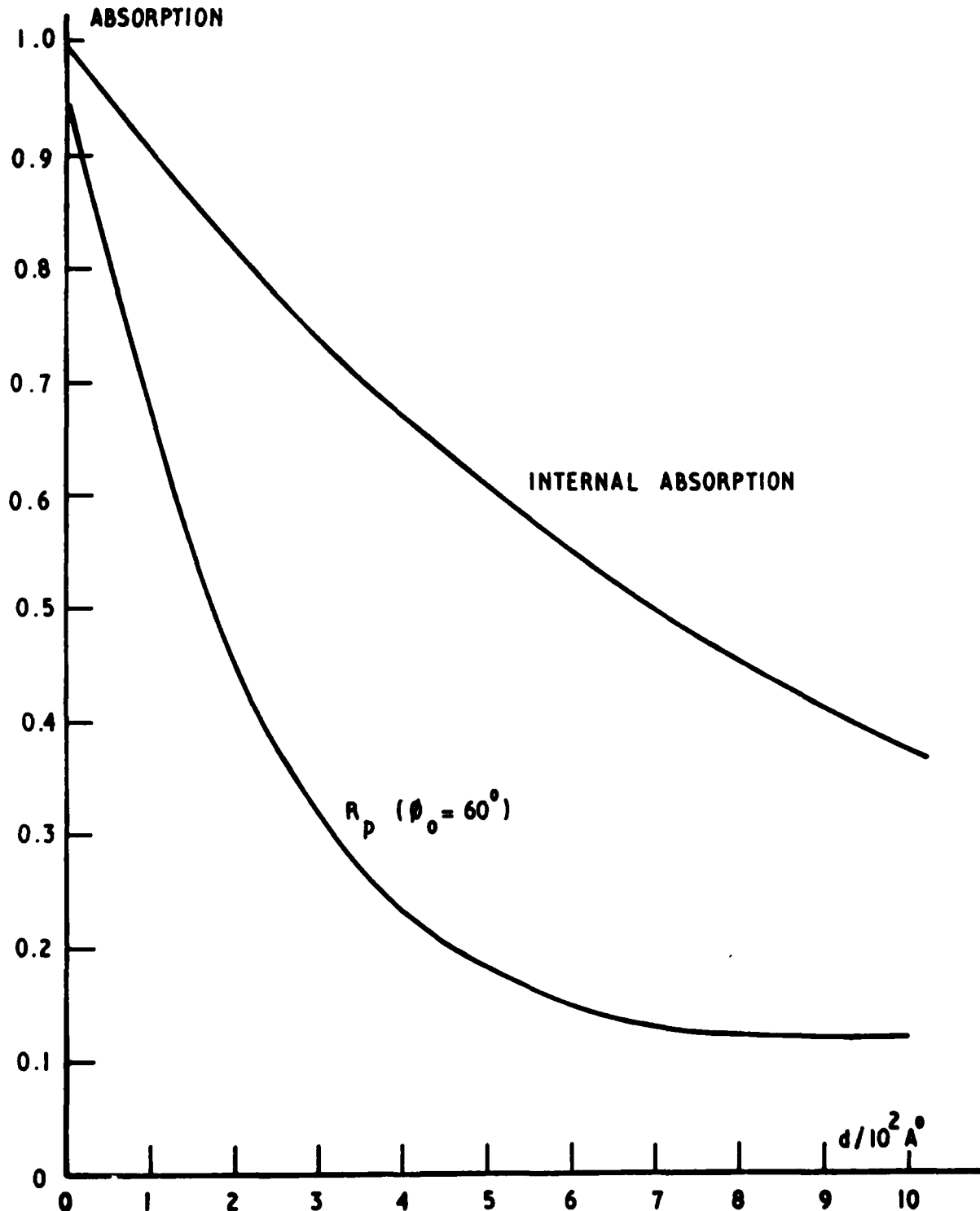


FIG. 4. VARIATION OF R_p AND INTERNAL ABSORPTION WITH THICKNESS FOR ALUMINIUM OVERCOATED WITH SiO AT A WAVELENGTH OF $8.8 \mu\text{m}$

LIST OF ABBREVIATIONS, SIGNS AND SYMBOLS

R	Total reflectivity for unpolarised light
R_p, R_s	Reflectivity components for light parallel and perpendicular to the plane of incidence
ϕ_o	Angle of incidence
n	Refractive index
k	Extinction coefficient
N	Complex refractive index ($N = n - ik$)
ψ	Phase change on reflection of light
ϕ'	See definition in section 2
ϕ_1	Angle of refraction in coating
r	Ratio of the reflected to incident amplitudes of the electric vector of an electromagnetic wave (the Fresnel coefficient)
g, h	Real and imaginary parts of r
d	Thickness of the coating
λ	Wavelength of light

